Available online at www.sciencedirect.com
SCIENCE DIRECT®

Renewable and Sustainable Energy Reviews
8 (2004) 223–236

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Contribution of fractures to formation and production of geothermal resources

Mineyuki Hanano *

Japan Metals & Chemicals Co., Ltd., 8-4 Koami-cho, Nihonbashi, Chuo-ku, Tokyo 103-8531, Japan

Received 28 October 2003; accepted 31 October 2003

Abstract

Heat, fractures and fluid are the fundamental elements of geothermal resources. From a different viewpoint, existence of natural hydrothermal convection to form convective geothermal resources, and fluid production from wells, are the important factors for geothermal development. Under this circumstance, fractures play two different roles. One is contribution for the onset of the natural convection in geothermal systems, and the other is contribution as flow paths to connect wells to the reservoir for fluid production. Since the inter-fracture ascending velocity of natural convection in geothermal reservoirs is of the order of 10^{-8} m/s, fractures from very small to very large permeabilities contribute to the first role. However, in-flow velocity of single-phase liquid within fractures in the vicinity of the well face ranges from 10^{-1} to 10^{1} m/s for example. Thus, only fractures of very high permeability can contribute to the second role. Therefore, one should always note the roles of fractures when discussing permeability in geothermal reservoirs.

Keywords: Geothermal resource; Geothermal reservoir; Fracture; Permeability; Natural convection; Well production

Contents

* Tel.: +81-3-3667-6534; fax: +81-3-3669-1972.
E-mail address: hananom@jmc.co.jp (M. Hanano).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2003.10.007

1. Introduction

Geothermal resources currently developed for large-scale commercial electric power generation are characterized by the existence of natural convection within the systems. (1) Heat (2) fractures (3) fluid are the fundamental factors required for the formation of the convective geothermal resources and for the heat extraction from the reservoirs.

Among them, the heat is the geothermal energy itself. It also enables the onset of natural convection by giving buoyancy resulting from the reduction of fluid density caused by thermal expansion. It also helps the onset of natural convection by reducing viscosity of the fluid. These effects caused by high temperature make the onset of natural convection easier by 10 times and more [1].

The fluid is the transport material for the heat. It transports heat energy as sensible and/or latent heat.

The fluid flows through fractures in rocks. Permeability of geothermal reservoirs is usually caused by fractures of various lengths and widths [2: p. 66]. Therefore, importance of fractures in geothermal development has been well understood especially in engineering circles.

In this paper, I will point out that there are two different roles of fractures in geothermal development: (1) contribution to occurrence of natural convection in geothermal systems to form convective geothermal resources, and (2) contribution to high degree of permeability around wells which enables in-flow with low enough flow resistance at a very high flow rate. Also, I will discuss relationship between sizes of fractures and each role.

2. Contribution to formation of geothermal resources

2.1. Natural hydrothermal convection in geothermal systems

Geothermal reservoirs are always located within zones of upflow in hydrothermal convection systems [2: p. 16]. One of the reasons is its higher rate of heat transport from great depth, compared with that of heat conduction. Another reason is its higher temperature at shallower depths, compared with those of conductive geothermal systems.

Temperature profiles of wells in and around the Kakkonda geothermal field, Japan are shown in Fig. 1. Refer to [3–7] for details of the Kakkonda geothermal

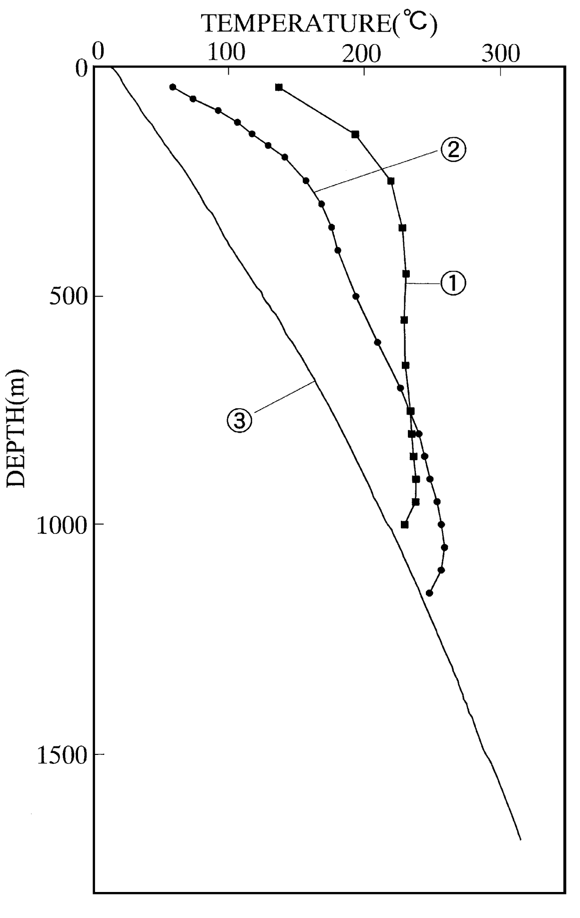

Fig. 1. Temperature profiles of three wells in and around Kakkonda geothermal field, Japan [4]. Locations of the wells are shown in [4].

system. Well (1) in Fig. 1 is a typical production well in the Kakkonda shallow reservoir. Its temperature profile indicates the existence of active upflow. Since the natural ascending volume flux (i.e. Darcy velocity) in natural state is 5×10^{-9} $m^3/s\ m^2$ [5,6], the inter-fracture ascending velocity in the natural state of the Kakkonda shallow reservoir is about 5×10^{-8} m/s. Thus, fluid needs approximately 600 years to vertically ascend 1 km in the reservoir. In this case, the temperature of the ascending liquid is approximately 230 °C. Thus, the heat flux associated with the ascending flow is approximately 4 W/m^2, because density and specific enthalpy of the ascending hot water are 830 kg/m^3 and 990 kJ/kg, respectively.

On the other hand, well (3) is located about 5 km away from well (1). There does not exist active hydrothermal convection at the location of well (3), so that the heat transport is dominated by the heat conduction. Since the temperature gradient at well (3) is about 0.2 K/m, the heat flux is approximately 0.4 W/m^2, assuming that the thermal conductivity of the rock medium is about 2 W/m K. This is only 10% of that of the location of well (1).

Temperature of well (3) reaches 300 °C at 1.5 km depth, which is higher than that of well (1) with the same depth. However, due to the lack of natural hydrothermal convection, the heat flux at the location of well (3) is only 10% of that of well (1), as described above. Based on this fact, natural hydrothermal convection is absolutely needed to transport large enough heat from great depth to exploitable depth for commercial utilization. Recent study indicates that ascending velocities in various convective geothermal reservoirs are of the same order of magnitude [8,9].

It is well known that permeability and buoyancy are the key parameters for the onset of the natural convection in porous media [10: p. 404]. The natural convection may not occur if one of the two factors is not sufficient, though the other is large enough. In the case of well (3), there may be large enough buoyancy, because temperature at 1.5 km depth is 300 °C. Therefore, the lack of permeability is the reason why natural hydrothermal convection does not exist at the location of well (3).

2.2. Permeability required for the evolution of hydrothermal convection systems

Necessary level of vertical permeability for the onset of natural convection in geothermal reservoirs of about 200–250 °C is approximately 10^{-15} m^2 [11]. This means that this level of permeability is required as an average of the entire system to form convective geothermal resources. This level of permeability is easily obtained when we test core samples which contain networks of small open fractures [12: p. 522]. This minimum required permeability is reduced to about 10^{-16} m^2 when the reservoir temperature is 350 °C because of enhancement of buoyancy and reduction of fluid viscosity.

Permeability of geothermal reservoirs is caused by fractures of various lengths and widths as described above. Since the theoretical relation between permeability k and aperture of an ideal flat open fracture b is $k = b^2/12$ [13], theoretical aperture of an open fracture which gives permeability of 1.0×10^{-15} m^2 is

1.1×10^{-7} m. It is very thin, thus there are countless number of such small fractures within geothermal reservoirs.

At the location of well (3) in Fig. 1, there must be a lot of such small fractures. However, they may be filled with minerals and/or they are not connected to each other. Thus, there is not sufficient network of permeability for the onset of natural convection around well (3).

The ascending velocity of upflow within fractures in geothermal reservoirs is in the order of 10^{-8} m/s as described above. This is very slow. Thus, such a slow fluid flow may exist within fractures of the very thin aperture calculated above. This suggests that fractures of such a low permeability can contribute to the onset of natural convection in geothermal systems. Of course, fractures with larger permeabilities can also contribute to the onset of the natural convection. Thus, almost all the fractures in geothermal systems, from very small to very large, as a whole, contribute to the onset of natural convection to form geothermal resources, which can be commercially developed. This is the first role of fractures.

3. Contribution to well production and injection

The second role of fractures is the contribution to well production and injection. That is, contribution to higher degree of permeability around wells, which enables in-flow and/or out-flow around the wells with low enough flow resistance at a very high flow rate.

3.1. Example of flow around a well

Fig. 2 is a spinner log during an injection test of a production well in a geothermal field in Japan. This well encountered a permeable fractured zone at around 2618 m depth and resulted in total loss of circulation. The spinner log indicates that all the injected water flowed into the reservoir through several fractures between 2672 and 2706 m depth. This is a very narrow interval compared with the total length of the open-hole section. It clearly indicates that the fluid flow into and/or out of the well occurs only through fractured zones which have very high permeability instead of the whole length of the well face, though so many small fractures intersect the whole length of the well face.

Fig. 3 shows photos of the Daifunto[1] of the Oyasu hot spring in Akita, Japan. In these photos, steam and hot water flow out only from the fractures developed in the cliff, i.e. fractures of sizes recognizable from a distance. Neither the steam nor the hot water flow out from the cliff wall where there is no visible fracture. This phenomenon reminds us the in-flow of geothermal fluid into the wellbore from the reservoir formation. In this case, the cliff wall is thought to be a well face of an open-hole section.

[1] Daifunto: a Japanese proper noun representing a flushing hot spring.

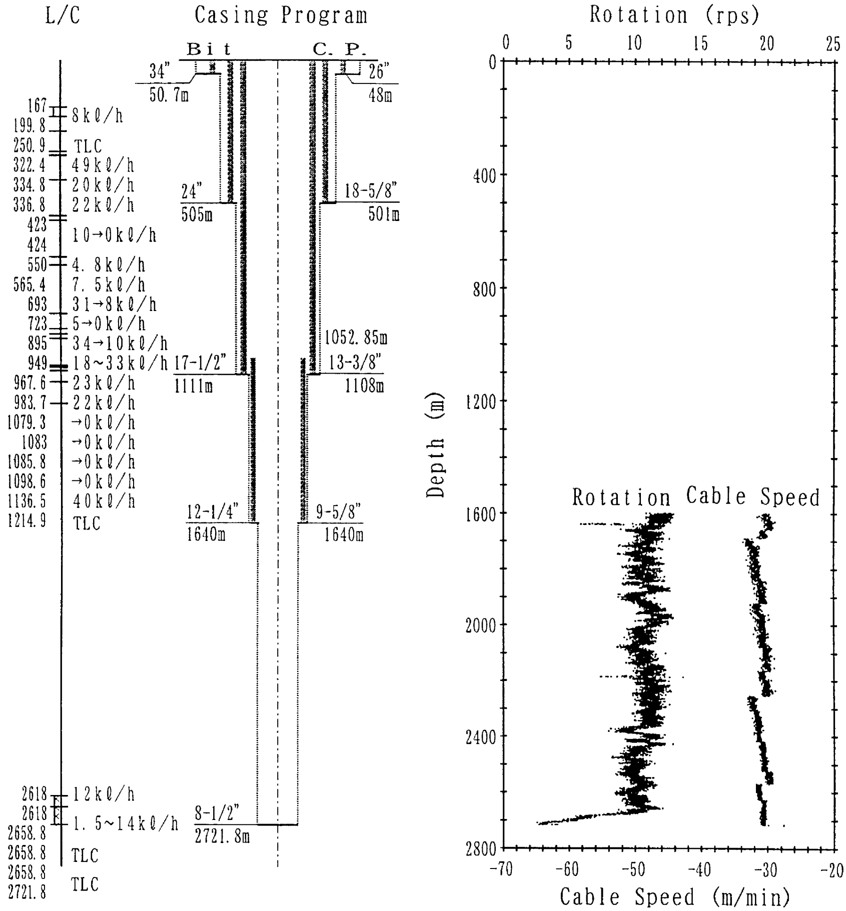

Fig. 2. Spinner log of an injection test of a production well. L/C, loss of circulation; TLC, total loss of circulation.

Based on the above discussion, we now have the following conceptual model. Fig. 4 is a schematic image of the in-flow in a well through a penny-shaped open fracture. Fluid flows only through the fracture which intersects the well, and then flows into the well. In this case, the in-flow through the fracture can be approximated to be a horizontal radial flow within a very thin space between flat parallel plates. Thus, the velocity of the in-flow becomes larger as the flow approaches the well (Fig. 4). The velocity is very high in the vicinity of the well but it is very low at a distance from the well. This suggests that the fracture needs very high permeability around the well but much lower permeability is sufficient at a distance. Thus, permeability distribution within the fracture needs not to be uniform. This is the characteristic of fractures which should be encountered by a well for successful

Fig. 3. Photos of Daifunto of the Oyasu hot spring, Akita, Japan (taken by Masayuki Tateno). Steam and hot water flow out from the fractures developed in the cliff. Neither the steam nor the hot water flow out from the cliff wall where there is no visible fracture. This phenomenon reminds us the in-flow of geothermal fluid into the wellbore from the reservoir formation.

fluid production. Fluid flows into the production fracture both vertically and horizontally, through fractures which intersect the production fracture, as a result of the pressure drawdown within the production fracture.

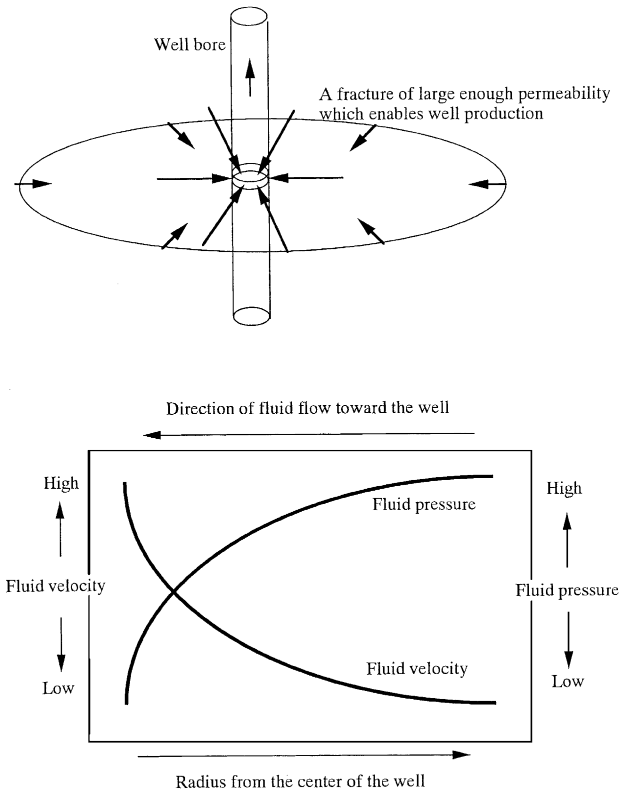

Fig. 4. Illustrated in-flow around a production well along with pressure and fluid velocity distribution within the production fracture.

3.2. In-flow velocity and permeability around a well

Let us consider steam production from a liquid-dominated geothermal reservoir of about 250 °C. Assuming that the steam production from a well is 50 t/h at well head pressure of 0.6 MPa abs., total production, i.e. steam and hot water, is about 250 t/h. In most cases under such a condition, the fluid flows into the well as single-phase liquid and then flashes in the wellbore. In this case, the horizontal radial inter-fracture in-flow velocity of the single-phase liquid is 10^{-1}–10^{1} m/s at the well face, assuming that there is only one production fracture intersecting the well and that the aperture of the fracture is 10^{-2}–10^{0} m and the diameter of the well is 216 mm (8.5 in.). This horizontal inter-fracture in-flow velocity is larger by 10^{6}–10^{8} than the inter-fracture ascending velocity of the natural convection of geothermal systems as described above. This clearly indicates that fractures which act as flow paths between reservoirs and wells should have very high permeability which

enables low enough flow resistance to permit such a high velocity in the fractures in the vicinity of the wells.

The permeability–thickness product (kh) of production wells in liquid-dominated geothermal fields obtained by single-well pressure transient tests ranges from 10^{-12} to 10^{-10} m^3 [2: pp. 160–233]. Thus, horizontal permeability of fractures related to fluid production from the production wells is 10^{-12}–10^{-8} m^2 assuming the same fracture aperture employed above. These values are 10^3–10^7 times larger than 10^{-15} m^2, which is the approximate minimum required vertical permeability for the onset of the natural convection in geothermal reservoirs, as described above.

This result clearly indicates that fractures with permeabilities lower than 10^{-12}–10^{-8} m^2 are unable to act as the flow paths to connect wells to reservoirs for commercial steam production. Thus, they cannot be feed zones of wells. This is because their flow resistance is so high that they are unable to sustain high enough fluid velocity for fluid production because of too large pressure drawdown. However, it is necessary to note that the permeability values, 10^{-12}–10^{-8} m^2, are acceptable only for the case discussed above, and are not necessarily representative of the actual productive fractures, because the values strongly depend on fluid temperature, fluid pressure, number of productive fractures and aperture of the fractures.

3.3. *Is production always possible within convective geothermal reservoirs?*

It is well known among geothermal field engineers that wells with heat conductive temperature profiles may not produce large amount of geothermal fluid constantly for a long time, for commercial power generation. Thus, all the production wells for commercial geothermal power generation are drilled within geothermal reservoirs which are parts of natural hydrothermal convection systems.

Therefore, is steam production always possible from wells drilled in convective geothermal reservoirs? The answer is no. Fig. 5 shows the temperature profiles during the warm-up after drilling of a production well in a geothermal field in Japan. It is clear that there exists a natural hydrothermal convection in this reservoir. Thus, the reservoir is made of fractured porous media whose bulk average of vertical permeability is greater than 10^{-15} m^2. Thus, the fractures in the reservoir make up a network to allow convective fluid circulation in the reservoir. However, the well did not encounter any fracture which could cause total loss of circulation or that of similar permeability during the drilling of its open-hole section, as seen in the lost circulation record (Fig. 5). Therefore, the well was not productive. This clearly indicates that a drilling target should be carefully examined even in a convective geothermal reservoir.

Fig. 6 shows well M-12 in the Matsukawa geothermal field, Japan, which is an extreme example of this phenomenon. Matsukawa is a vapor-dominated geothermal field where there is a very active hydrothermal convection in the reservoir [15,16]. Well M-12 was a deviated well and drilled into its primary target zone shown as a circle with a diameter of 20 m. However, it did not encounter any productive fracture in the circle and was drilled through the target zone without any loss of circulation. The open-hole section of well M-12 was back-filled and

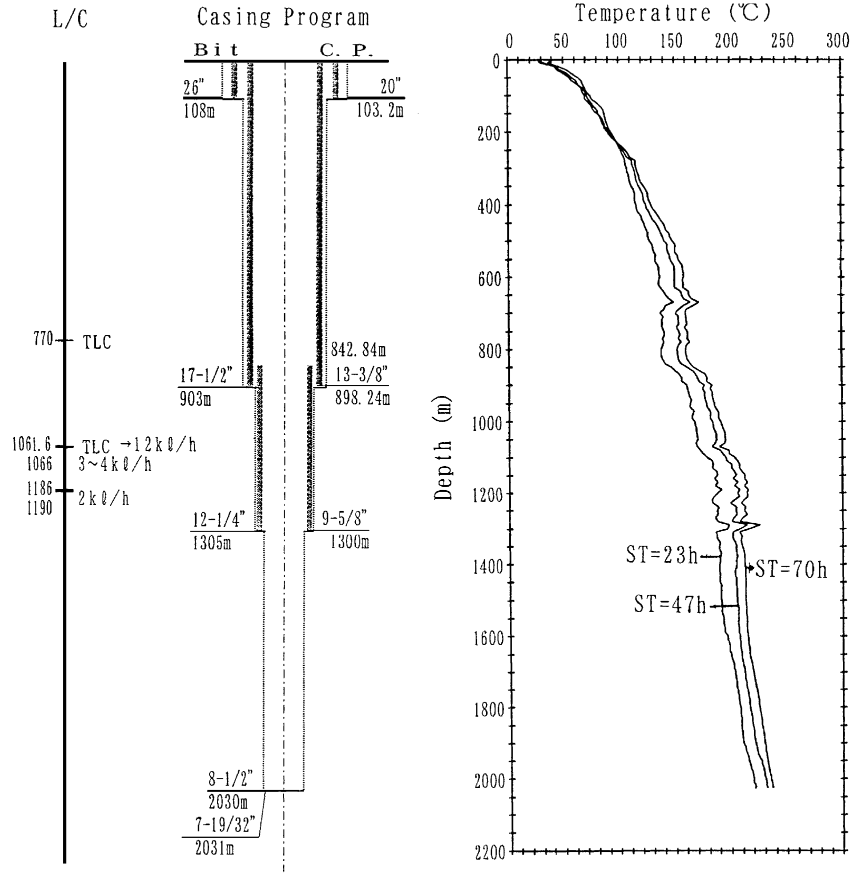

Fig. 5. Example of an unproductive well drilled in a convective geothermal reservoir. L/C, loss of circulation; TLC, total loss of circulation; ST, standing time.

cemented. Then, the well was side tracked from the bottom of the casing pipe. The side-tracked leg encountered a productive fracture which caused total loss of circulation, right after the start of the side-track.

However, we have to note that the total loss of circulation was located in the target circle of which the original leg was drilled through without any loss of circulation. The three-dimensional distance between the loss of circulation in the side-tracked leg and the original leg was only 10 m. This clearly indicates that the number of productive fractures is limited, and so is their distribution, even though there is an active hydrothermal convection in the reservoir.

Based on the above discussion, we may summarize the contribution of fractures to well production and injection, as follows. There are a large number of fractures of different lengths and apertures, i.e. different permeabilities, in geothermal reservoirs. However, only the fractures of high enough permeability, which ensure low

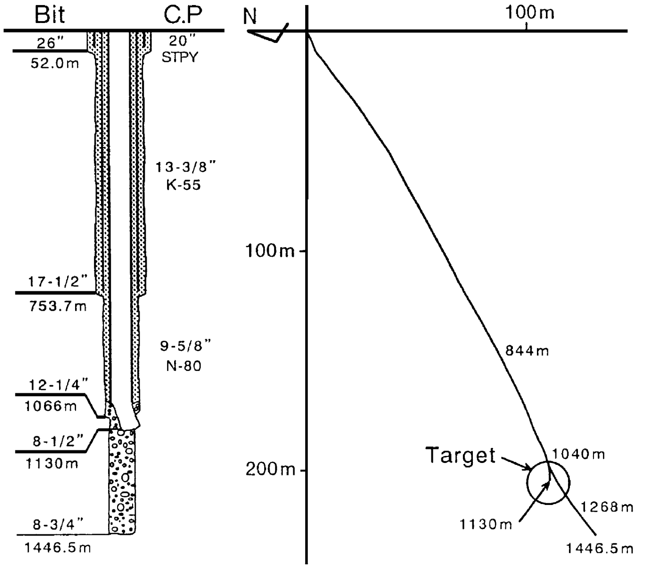

Fig. 6. Drilling target and results of well M-12 in Matsukawa geothermal field, Japan [14].

enough flow resistance for the in-flow around wells, can act as flow paths from the reservoir to the wells for fluid production, though many fractures intersect well walls. All other fractures of lesser permeability cannot act as flow paths because of too large pressure drawdown due to a too large flow resistance. That is, no matter how large the number of fractures with low permeabilities that intersect a well, the well cannot be productive. Commercial steam production is not possible if a well does not encounter a fracture of large enough permeability, even though the well is drilled within a convective geothermal reservoir. It is only possible when wells encounter productive fractures which cause large amount of loss of circulation. This is the second role of fractures.

4. Sizes and permeabilities of fractures for the onset of natural convection and well production

There are many fractures of different size, i.e. lengths and apertures, and permeabilities in the reservoir. The number of large fractures (i.e. larger permeabilities) is less than that of small fractures (i.e. less permeabilities). Their relation is fractal [17: pp. 44–50]. The relation between the number of fractures N and the size of fractures, i.e. the permeabilities of the fractures, is illustrated in Fig. 7. As described above, the permeability of a fracture is related to the fracture aperture. Since the fracture aperture is usually proportional to the length of the fracture, the fracture length L is used as the horizontal axis in Fig. 7.

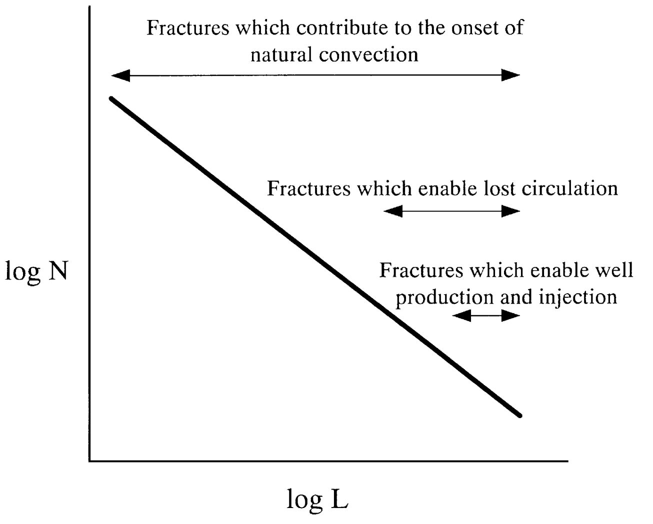

Fig. 7. Schematic relationship between fractures of various lengths and roles of fractures. Thick solid line: relationship between fracture lengths and number of them. N, number of fractures; L, length of fractures.

As discussed above, the minimum permeability needed for the onset of natural convection in geothermal systems is relatively low. Thus, almost all fractures from very small to very large can contribute to it (Fig. 7). However, only fractures of high enough permeability enable well production, as already said. Therefore, the fractures which can contribute to the well production are limited to those with high permeability (Fig. 7). These fractures cause large loss of circulation, when they are encountered during drilling.

Relatively smaller loss of circulation also occurs when the well encounters fractures slightly smaller than the productive ones. Thus, the fractures, which cause the loss of circulation, have a slightly wider range in size, i.e. permeability, than that of the productive fractures (Fig. 7).

Geothermal exploration is usually carried out in two steps. The first step is a reconnaissance survey to delineate the geothermal reservoir, the second step is the selection of the drilling target for steam production and injection. The purpose of the reconnaissance survey is to delineate a high-temperature ascending flow zone within a hydrothermal system. Thus, it is related to the first role of the fractures. On the other hand, the second step involves locating high permeability fractures within a geothermal reservoir. Thus, it is related to the second role of the fractures. Therefore, the two different roles of fractures are the main reason which explains why geothermal exploration is conducted in two steps. Reminding the two roles of fractures may give beneficial insight when planning geothermal exploration in geothermal fields. Also, this concept is a necessary background when discussing permeability related phenomena in geothermal reservoirs.

5. Conclusions

Heat, fractures and fluid are the three fundamental factors required for the occurrence of convective geothermal resources and for the heat extraction from the reservoir. From a different viewpoint, the most important factors for the conventional geothermal development are: the existence of a natural hydrothermal convection to form liquid- or vapor-dominated geothermal resources, and a fluid production from wells to supply steam and/or hot water for commercial utilization.

From the above discussion, we can conclude that fractures play two different roles in geothermal development: (1) a contribution to the onset of natural convection in geothermal systems to form geothermal resources. This is given by almost all the fractures from very low to very high permeabilities. (2) A contribution to the flow path to connect wells to the reservoir to let the fluid flow into and/or out from the wells. This is given only by fractures of high enough permeability. This concept is a fundamental characteristics of geothermal reservoirs and steam production. One should always realize the importance of the roles of fractures when discussing permeability in geothermal reservoirs.

Acknowledgements

A preliminary version of this paper was presented at the World Geothermal Congress 2000, in Japan. I would like to thank the management of Japan Metals & Chemicals Co., Ltd. (JMC) for their permission to publish this paper, the colleagues at JMC and JMC Geothermal Engineering Co., Ltd. for their daily discussions, and the referees for their review of the manuscript.

References

[1] Garg SK, Kassoy DR. Convective heat and mass transfer in hydrothermal systems. In: Rybach L, Muffler LJP, editors. Geothermal systems. New York: Wiley; 1981. p. 37–76.

[2] Grant MA, Donaldson IG, Bixley PF. Geothermal reservoir engineering. New York: Academic Press; 1982. p. 369.

[3] Nakamura H, Sumi K. Exploration and development at Takinoue, Japan. In: Rybach L, Muffler LJP, editors. Geothermal systems. New York: Wiley; 1981. p. 247–72.

[4] Hanano M. Hydrothermal convection system of the Kakkonda geothermal field, Japan. Proceedings of the World Geothermal Congress, Florence, Italy. 1995. p. 1629–34.

[5] Hanano M. A simple model of a two-layered high-temperature liquid-dominated geothermal reservoir as a part of a large-scale hydrothermal convection system. Transport in Porous Media 1998;33(1):3–27.

[6] Hanano M, Kajiwara T. Permeability associated with natural convection in the Kakkonda geothermal reservoir. Transactions of the Geothermal Resources Council 1999;23:351–60.

[7] Special issue on deep geothermal systems-Japanese national project at Kakkonda. Geothermics 1998;27(5/6).

[8] Kato M, Kaneko K, Hanano M. Velocities of convective ascending flow in liquid-dominated hydrothermal convection systems. Proceedings of the 24th Workshop on Geothermal Reservoir Engineering, Stanford University. 1999. p. 164–7.

[9] Kato M, Hanano M, Kaneko K. Velocities of convective ascending flow in geothermal systems based on static temperature logging data analysis and simulation study. Proceedings of the World Geothermal Congress, Kyushu, Tohoku, Japan. 2000. p. 2647–52.
[10] Turcotte DL, Schubert G. Geodynamics. New York: Wiley; 1982. p. 450.
[11] Straus JM, Schubert G. Thermal convection of water in a porous medium: effects of temperature- and pressure-dependent thermodynamic and transport properties. Journal of Geophysical Research 1977;82(2):325–33.
[12] Yano Y, Suda Y, Tamanyu S. Well data compiled from Japanese nation-wide geothermal surveys, part 1: core sample data—physical properties, geology, age, chemical composition. Report no. 271, Geological Survey of Japan; 1989. p. 832.
[13] Witherspoon PA, Wang JCY, Iwai K, Gale JE. Validity of the cubic law for fluid flow in a deformable rock fracture. Water Resources Research 1979;16:1016–24.
[14] Saito S. Recent geothermal drilling activities and technologies in Matsukawa, Kakkonda and Mori, Japan. Journal of Japan Geothermal Energy Association (Chinetsu) 1990;27:325–55 [in Japanese].
[15] Hanano M, Kotanaka K, Ohyama T. A quarter century of geothermal power production at Matsukawa, Japan. Geothermal Resources Council Bulletin 1993;22:32–47.
[16] Hanano M. Sustainable steam production in the Matsukawa geothermal field. Geothermics 2003;32(3):311–24.
[17] Turcotte DL. Fractals and chaos in geology and geophysics. Cambridge University Press; 1992. p. 221.